

Lane Reservation for Highways (Position Paper)

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Abstract—The only way to keep up with the ever-increasing number of cars on roads is through constant change and improvement in the transportation infrastructure. Construction of new roads is constrained by space and financial resources. Therefore, there is a need to devise ways to make optimal use of the existing infrastructure. In this position paper, we describe a lane reservation system for highways. The idea is to allow drivers to reserve a slot on a high-priority lane by paying a premium price. The high-priority lane would provide congestion free travel between any two points on the highway. We describe the design of our system, the challenges that need to be solved and the evaluation methodology we are planning to adopt.

I. INTRODUCTION

Modern highways are extremely successful in providing high-speed arterial routes along frequented corridors. Under good conditions, traveling these highways is the fastest option for many drivers. Unfortunately, highways are also victims of their own success. As they are popular with commuters, they are subject to over subscription, and congestion is the largest problem faced by the highway infrastructure. Compared to other transportation methods, e.g., commuter rails, buses, etc., highways are unable to provide a guarantee, in terms of traveling time, to the commuter.

It is our position that we should incorporate the time guarantees of other popular means of commuter travel into the highway system, while maintaining the convenience of automobile travel. Our goal is to provide *differentiated services* on highways, allowing “higher-priority” traffic a means to negotiate a guarantee on the duration of their trip without substantial reduction in their ability to reserve departure times or travel routes. This approach is inspired by train and airline reservations. Unlike airlines and rails, though, drivers are accustomed to a certain level of flexibility in their travel, which they are unwilling to compromise. Therefore, any reservation system for highways must preserve the flexibility drivers currently experience, allowing them to make even last moment decisions about routes and highway entry times.

Our idea is to allow drivers to reserve an “entry slot” onto dedicated lanes of a highway by paying a premium price. Reservations are allowed for these lanes up to their carrying capacity, so that the system can provide a guaranteed duration to the driver between any two highway points, in the absence of automobile accidents. There are two key observations, which motivate this idea: (i) the time for a commuter to reach a highway is typically predictable, so it is easy for him to make a reservation in advance, most of the time, and (ii) people are willing to pay more in return for a shorter, guaranteed travel time.

The *Intelligent Lane Reservation System* for Highways (ILR) we propose is enabled by cutting-edge vehicular technologies, including vehicular computers and networking. The system is intelligent in a variety of ways. First, it allows users to place reservations through traditional on-line mechanisms (e.g., from a home computer over the Internet) or through emerging technologies (e.g., broadband connected mobile devices) on-the-road. Second, once a reservation is granted, the system will track the reservation and notify the user when he is allowed to enter the highway (through their mobile device). Finally, enforcement will be handled through two separate, complementary mechanisms: (i) infrastructure-based cameras and RFID readers, and (ii) vehicle-to-vehicle communication.

The mechanisms described in this paper are inspired by well-known techniques from computer network traffic management and real-time communication (e.g., packet scheduling, congestion control/avoidance techniques, and Quality of Service mechanisms). It is our position that similar techniques can be applied to the problem of traffic control. By providing congestion free travel for drivers, we believe we can solve the problem for those drivers most negatively affected by this problem, commuters.

This position paper is organized in the following fashion: The next section (Section II) describes our model. Section III provides an overview of our current design for the ILR system along with the challenges posed, while Section IV discusses security and privacy aspects. A description of our planned evaluation methodology is detailed in Section V, while Section VI describes the related work in the area. Section VII presents our conclusions.

II. MODEL

Consider the following scenarios:

Bob has to take Highway X to travel between work and home. Highway X is almost always congested. Therefore, Bob wastes an extra hour in his commute between work and home everyday.

Nancy has a court appearance on Tuesday evening for which she has to drive through Highway X. She is afraid of getting stuck in traffic and missing her appointment.

In the first scenario, Bob belongs to the category of frequent drivers. He would like to be given a higher priority over other passengers on Highway X and allowed to travel on a high-speed lane dedicated for passengers like him. Nancy, on the other hand, occasionally drives on Highway X. But under the circumstances, she would willing to pay a much

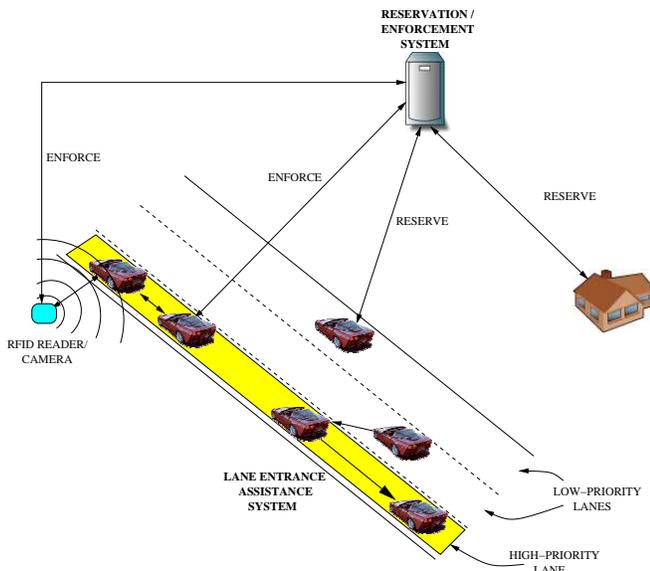


Fig. 1. System Overview. This figure illustrates the three major components of the ILR prototype system: (i) Reservation System, (ii) Lane Entry Assistance System, and (iii) Enforcement System. Additionally, the various system interactions are shown.

higher price to get on the high-speed lane than Bob would be.

It is quite clear that a *reservation system* is needed to handle the case of Bob and Nancy. Perhaps, people like Bob should be allowed a slot on the *high-priority lane* at a relatively low price, while people like Nancy should be allowed to buy slots for emergency situations at a higher price. The reservation system is accompanied by a corresponding *enforcement system*, which ensures that only drivers with valid reservations travel on high-priority lanes.

In addition to a reservation and an enforcement system, a system for assisting the driver with entering and exiting the high-priority lane is needed. This is because the high-priority lane is also a high-speed lane and will usually be utilized at maximum capacity. It is hard for a car to enter this lane without disrupting the traffic behind. The *lane entrance assistance system* helps drivers in entering the high-priority lane with minimal disruption of traffic, thereby maintaining quality of service. The *lane exiting assurance system* guarantees that the exit ramp capacity (for the priority lane) is never exceeded.

Finally, we envision the need for an *exception handling system*, which handles exceptional cases making intelligent lane reservation robust to real-life conditions. These include canceling, reimbursement, and reassignment of reservations, or handling of accidents on the high-priority lane.

Figure 1 shows the model consisting of three of the five key components: reservation system, lane entrance assistance system, and enforcement system. The reservation system is an online service, which is invoked from a home PC (for advance bookings) or a 3G-enabled mobile device (for on-the-spot reservations). The lane entrance assistance system is based on vehicle-to-vehicle communication. The enforcement system is implemented through the use of RFID,

cameras, and wireless communication.

III. DESIGN

In what follows, we describe the design options for the five key components of ILR and the design issues therein.

A. Reservation System

The reservation system is responsible for issuing tickets or tokens to drivers for traveling on the high-priority lane. Using this online system, users specify the time, date, and section of the highway for which they would like to make a reservation, and the reservation system issues a ticket/token to them. The rest of this section describes alternative reservation system policies.

Reservation Policy 1: The user specifies the date, time, and section of the highway and the system offers the user a number of slots (possibly depending on vehicle size), each priced on the basis of the demand for that slot. We call this *one-leg reservation*. The user can also specify the source and destination and ask the system to display the best combinations of slots on multiple highways that minimizes travel time. We call this *multi-leg reservation*. In the case of multi-leg reservation, the user *purchases* multiple slots (across highways) under one single reservation. The user can also buy a *persistent slot* on a highway, which is valid for a certain time period, such as a week, month, or year at a discounted price. In either case, the reservation system issues a digital-ticket to the user as a proof of the purchase. We discuss the different ways in which the digital-ticket could be implemented in the section on the enforcement system.

Reservation Policy 2: Under this policy, the system favors frequent drivers. Favoring frequent drivers provides an equitable and fair distribution of the total high-priority lane capacity across highways. It also helps by uniformly distributing traffic across different highways (in much the same way as congestion pricing [1]). The identification of frequent drivers is accomplished based on their location traces. The user submits a request for a slot or multiple slots and provides her location traces along with it. The location traces serve as proof that the user travels on certain highways at certain times of the day on a regular basis (e.g., between home and work). The reservation system takes the driving patterns (as indicated by the location traces) into account when the demand for reservation is more than the capacity of the high-priority lane. For this policy, the users equip their cars with a GPS receiver (that would record location) and a tamper-proof device that collects and signs the location traces to prevent tampering.

The location traces also help in minimizing human-computer interaction. Instead of manually specifying/requesting slots, the user submits her location traces, and asks the system to generate a set of slots that minimizes her travel time.

Reservation Policy 3: In addition to making advance bookings (under policy 1 or 2), the driver is able to make reservations on-the-fly directly on the highway, if slots are

available. This requires a client on the car PC (or the mobile phone) and Internet connectivity (e.g., through 3G).

Design Issues: A one-time slot is specified as a tuple: $\langle \text{date, time, highway section} \rangle$ (e.g., $\langle 06/11/2007, 5.30-6.30\text{pm, US 1 North Exit 9-11} \rangle$). A driver with that slot can travel on the high-priority lane of US 1 North between Exits 9 and 11 on 06/11/2007 between 5.30-6.30 pm, after which the slot would expire. A recurring slot is defined as: $\langle \text{period, time, highway section} \rangle$ (e.g., $\langle 06/2007, 5.30-6.30\text{pm, US 1 North Exit 9-11} \rangle$). This reservation enables the driver to use the high-priority lane for the entire month of June 2007.

The reservation system employs a game-theoretic algorithm for setting prices of different slots for different highways, based on the number of requests. For multi-leg reservation, a dynamic algorithm is employed for generating the best concatenation of slots across highways. A sub-component handles reservation cancellations and changes. The reservation system based on policy 2 incorporates a mechanism for verifying the authenticity of the location traces (or just the “Frequent Driver ID” of the driver). User routes are recorded in user profiles and are used for extracting individual and overall driving patterns. This has privacy implications.

The reservation system based on policy 3 handles on-the-fly reservations. A driver may demand a slot on a certain section of the highway on-the-spot. The reservation system may assign a slot to the driver, if the high-priority lane is under-utilized. For this, the reservation system has a component that monitors the occupancy of high-priority lanes. The monitoring component is closely tied with the enforcement component.

B. Lane Entrance Assistance System

Cars in the high-priority lane travel relatively high-speed (yet complying with speed limits) in order to best utilize lane capacity. In particular, the speed may be quite higher than in the regular lanes, especially when the latter are congested. This makes it challenging to enter the priority lane without disrupting the on-coming traffic. The lane entrance assistance system helps drivers to enter the high-priority lane with minimal disruption of traffic. It is worth noting that the lane entrance assistance system is not crucial to ILR and its only goal is to maintain quality of service, where quality of service is defined as the safety and travel time on the high-priority lane. The lane entrance assistance system is based on inter-vehicular communication and the rest of this section describes alternative system policies.

Lane Entrance Policy 1: All digital-tickets carry sequence numbers. A car wanting to enter the high-priority lane transmits, via radio, a *request to yield* along with its sequence number. The on-coming cars on the high-priority lane upon receiving the request, pass it back a few hops, perhaps up to 1 km. The recipients then start an election, in which the first car with a higher sequence number (within a prefix) sends a *yield acknowledge* message along with its sequence number and visual, as well as, electronic identity back to the original sender (via cars in front). The driver of the yielding car then

slows down and allows the new car to enter the high-priority lane in front of it. The larger the difference in speeds between the two lanes, the larger the interval. Also, the yielding car transmits a *slow down* message to notify the cars behind. Note that under this scheme, cars in the “platoon” are ordered (within the prefix) by sequence numbers (car with sequence number X is always behind a car with sequence $< X$). Also, a car must yield only to cars with lower sequence numbers. This procedure requires careful interaction between driver and the assistance system.

Lane Entrance Policy 2: Assigning and maintaining sequence numbers increases the cost and complexity of the system. A simpler assistance policy is to allow cars to enter the high-priority lane in any arbitrary order. A car wanting to enter the high-priority lane transmits a *request to yield*, and the first car to receive this request would have to slow down and allow the new car to enter the lane. The main purpose of the lane entrance assistance system is to coordinate lane-entering and minimize collisions using inter-vehicular communication. In this case, some coordination among drivers is required, so that only one slows down and lets the new vehicle in the lane.

Design Issues: The sequence numbers are highway and time specific, to prevent conflicts. The sequence number pertains to a slot and not to a reservation ticket, since one reservation ticket can contain multiple slots in the case of multi-leg reservation. Visual identity is the make, model, and color of the car along with its plate number. The visual identity is necessary for the new entrant to know when to enter the lane. Finally, to implement a lane entrance assistance system, an inter-vehicular communication protocol must be in place.

C. Lane Exit Assurance System

In order to provide an upper bound on the travel time, it is necessary to account for the time it takes to exit out of the high-speed lane. Exiting out of the high-speed lane may be troublesome if: (1) the regular lanes are jammed and hence getting to the exit is difficult, and (2) the exit itself is jammed. A possible workaround for (1) is to construct dedicated exits for the high-speed lane as is the case for car-pool lanes in some states in the U.S. In order to prevent (2), the lane exit assurance system must maintain statistics on the *exit rate* for each exit and accordingly decide the upper bounds on the number of cars that should be allowed to exit at any given exit location (exit capacity). This would serve to ensure that the exit capacity is not overloaded and consequently prevent exits from getting jammed. The lane exit assurance system is implemented as a subcomponent of the reservation system.

D. Enforcement System

The enforcement system serves to ensure that only drivers with a valid reservation travel on the high-priority lane. This section describes the alternative enforcement models (each with its own infrastructure requirements) for this system.

Enforcement Model 1: The reservation system issues a digital-ticket to the user, in the form of an online receipt

containing details of reservations. The users either print or electronically save this receipt as a proof of purchase. The reservation system saves the information corresponding to this reservation in a database. The highways are instrumented with digital cameras, which periodically take pictures of the license plates of cars traveling on the high-priority lane. The license plate numbers of the drivers are verified against the database containing reservation information and anybody found violating the law is ticketed.

Enforcement Model 2: The reservation system mails the user a cheap RFID tag (similar to the EZPass tag) containing reservation information with corresponding RFID readers (e.g., EZPass readers) installed on highways. This enforcement model works in much the same way as EZPass enforcement. Alternatively, police vehicles could be equipped with RFID readers. In either case, the vehicle ID number is verified (against a central database), via RFID, that the driver has purchased the ticket for that segment.

Enforcement Model 3: The reservation system issues a signed digital-ticket to the user either in the form of an SMS/MMS to the user's phone or as a file, which the user saves on the PC from which she is making the reservation and then later transfers to the car PC. When a driver enters a high-priority lane, other cars in the lane challenge them to present a valid signed digital-ticket over wireless communication. (Each car would be equipped with the corresponding reservation verification software.) If a car fails to present a valid reservation, their information will be passed on to the authority at the next network opportunity (such as a wireless access point). This is a peer-to-peer enforcement model.

Design Issues: Enforcement model 1 requires no infrastructure in the car, but cameras on the highway. Most of these cameras are dummy cameras to keep the drivers under check while others are real. Enforcement model 2 requires an RFID tag (e.g., EZPass) to be installed in the car, and RFID readers on the highway. Enforcement model 3 requires a car PC in the car or a mobile phone equipped with the necessary software and wireless networking capability. Intermediate wireless access points are needed on the highway (or 3G connectivity in cars) in order to pass the information onto the authority.

For enforcement model 1, algorithms for image processing are employed to automatically extract license plate information from the images. Enforcement model 3 uses an inter-vehicular ticket-exchange protocol.

The enforcement system also has a component for monitoring the occupancy of the high-priority lanes. This information is shared with the reservation system for handling on-the-fly reservations, as described earlier.

E. Exception Handling System

In order to provide high quality of service and certain guarantees with respect to travel time, ILR incorporates mechanisms for handling exceptions. These exceptions include canceling, reimbursement, and reassignment of reservations. The exception handling system also allows reservations to be

exchanged between drivers through the reservation system, either offline (e.g., from a home PC) or on the highway in real-time. Reservation exchange is based on mutual agreement between two drivers, and different from canceling a reservation and reissuing it to someone else.

In the event of an accident on the high-priority lane, the system needs mechanisms for re-booking reservation slots of drivers. This is further complicated if the driver has reservations on multiple highways, in which case she may miss all her assigned slots if the system does not take responsibility and re-book slots dynamically. The exception handling system shares components primarily with the reservation system and also with the lane entrance and enforcement system and we adopt an aspect-oriented approach, due to the cross-cutting nature of the system.

IV. SECURITY AND PRIVACY ISSUES

There are privacy issues surrounding the ILR system. In submitting the location traces, the users essentially surrender their location privacy to the reservation system. Unless the users are convinced of the trustworthiness of the reservation system, they may be reluctant to participate. Again, the enforcement system keeps track of the occupancy of the high-priority lanes and breaches the location privacy of the drivers. We have previously proposed a solution for preserving location privacy [2], which suggests the use of a trusted central server for maintaining location information and sharing this information with services (ILR in this case) in a manner that prevents the untrusted service from inferring private location information. This solution could possibly be extended and applied to address this problem.

The security issues are not as critical in this case but are important nevertheless. The lane entrance assistance system requires the new entrants to broadcast their sequence numbers, which can be forged unless a mechanism for signing and verification is employed. Similarly, if vehicle-to-vehicle enforcement is used, an ad-hoc mechanism for validating the authenticity of the digital ticket must be employed. Finally, all communication with the reservation/enforcement system must be encrypted with suitable public-private key pairs in order to counter "man-in-the-middle" attacks.

V. EVALUATION STRATEGY

This section describes our proposed methodology for evaluating the ILR system. For a large-scale system, such as ILR, to be adopted, it is imperative that a thorough study be performed to evaluate both the feasibility and performance for the system.

A. Implementation Plan

As described in Section II, the various components of ILR are distributed and interact with each other to provide the intelligent lane reservation service. The prototype ILR system will include all of the components described previously and shown in Figure 1. As shown in the figure, the reservation and enforcement systems will be built from

commodity hardware/software and export a web-based front-end (reservation system) for user over the Internet. The lane assistance system will be built from car PC's and mobile phones, as previously stated. Finally, the enforcement system will utilize car PC's/mobile phones, RFID tags and readers, and stationary road-side cameras.

B. Metrics

The goal of the ILR system is to provide time-based guarantees to drivers on the durations of their reserved trips. For this system to be widely adopted, the system must be perceived to be at least as accurate as similar time schedules in other forms of commuting (e.g., commuter rails, airlines, etc.). Therefore, the real-time performance of the ILR system must be evaluated with respect to reservation accuracy. We envision four important metrics that must be well-understood before ILR can be adopted in real highway environments: (i) best case performance, (ii) performance in the presence of exceptions, (iii) minimum or break-even performance, and (iv) performance relative to alternative approaches.

Best Case Performance: It may not be necessary to achieve the “best possible” accuracy in ILR. It is likely to be sufficient that the system meets some minimum accuracy on average. In other words, the system will meet user expectations so long as it is *perceived* to be accurate by the users, on the whole. A key output from the evaluation will be to determine this minimum accuracy, under the best possible conditions.

Performance with Exceptions: To understand all aspects of the ILR system, it is equally important to evaluate the performance under less than ideal situations. Accidents, break-downs, etc., will still occur, and the system is designed to handle these situations when they arise. Therefore, to be thorough, the evaluation will measure system performance in the presence of exceptions. Primarily, this portion of the evaluation will study the sensitivity of the system to various types and durations of exceptions.

Break-even Performance: In partitioning a highway into high-priority and lower-priority lanes, we are reducing the capacity for the lower-priority traffic to increase the capacity for the high-priority traffic. In doing so, we run the risk of increasing congestion in the lower-priority lanes for minimal improvement in the high-priority traffic flow. This situation can arise if the high-priority lanes are under-subscribed, for example due to high price of reservations, privacy issues, etc. This portion of the evaluation will attempt to determine the level of subscription (utilization) required in the high-priority lanes for the system to satisfy both the conditions: (i) to meet the guarantees provided by ILR reservations and (ii) to not increase the average trip duration for the lower-priority traffic.

Relative Performance: Finally, the ILR system will be compared to alternative traffic management solutions. The Congestion Pricing system [1] attempts to manage traffic by increasing or decreasing highway toll rates based on the level of congestion on the highway. Although we believe that Congestion Pricing is a complementary approach to

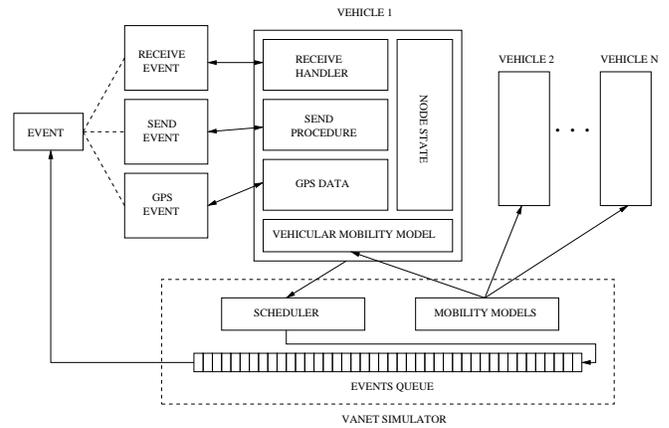


Fig. 2. VANET Simulator Architecture. This figure illustrates the major components of the VANET simulator. Each simulated vehicle interacts with the event scheduler and mobility module to accurately emulate an application executing under realistic traffic scenarios.

ours, it would still be relevant to compare the relative performance of ILR to Congestion Pricing. Additionally, it would be interesting to consider the performance of hybrid systems, e.g., combining ILR and Congestion Pricing, in this evaluation.

C. Simulation Plan

Prior to any real world deployments, it is important to evaluate the ILR system through simulation. As discussed in Section III, there are a number of possible policies to choose between. It is unlikely to be feasible to evaluate all possible policies for each major system component in a real world deployment, so we will prune the worst performing by first simulating. Additionally, there are likely to be cases that can only be simulated since they are too difficult or costly to test in a real world test bed.

Accurate simulation of VANETs is in itself a challenging problem. Furthermore, there are no simulators available that provide all of the various components needed to explore the design space for ILR. In order to simulate our system, we are leveraging our previous work in the area of vehicular simulation [3] to emulate a ILR-like system. Unlike other network simulators (e.g., NS2 [4]), our simulator incorporates a mobility model for wireless nodes based on a traffic model that includes representations of real roadways and drivers' behavior.

Figure 2 describes the architecture of our VANET simulator. The primary advantage of this architecture is that it can execute (or emulate) the code of a real vehicular application without significant changes by using the interface described above. By utilizing this simulator to emulate ILR, we are able to rapidly evaluate a broad range of component policies (i.e., for reservation acceptance and cancellation, for admission control, and for enforcement) under realistic traffic scenarios. As a first step, we will focus on a simplified scenario where users may reserve a single-leg trip, consisting of only one highway. Our final goal, though, is to simulate multi-leg reservations combining numerous single-legs into a complete trip from origin to destination.

VI. RELATED AND PRIOR WORK

To the best of our knowledge, the idea of implementing and enforcing an intelligent lane reservation system is novel and unexplored. Lane reservation shares some goals with Congestion Pricing [1]. Congestion Pricing aims at equitable distribution of traffic across highways in order to handle congestion. This is achieved by setting toll prices for different highways in proportion to the level of congestion, in order to encourage drivers to travel on less congested roads. ILR also aims at handling congestion by prioritizing certain lanes on the highway. However, unlike Congestion Pricing which attempts to address the congestion of a roadway in a uniform manner, ILR provides differentiated service by introducing high-priority lanes to the roadway. The remainder of this section describes our experience and prior work in the area of Vehicular Computing, which we plan to leverage for this project.

We have built a system for traffic data dissemination and visualization in vehicular ad-hoc networks, called TrafficView [5], [6], [7]. TrafficView uses vehicle-to-vehicle communication to provide continuous updates about traffic conditions. The primary goal of this system is to assist the driver in route planning and driving under adverse weather conditions when visibility is low. This system is complementary to the approach described in this paper, and can be extended to implement the lane entrance assistance and enforcement systems.

We have developed a prototype, called EZCab [8], for decentralized cab reservation in cities. Unlike other existing solutions for inter-vehicle communication that are based on certain infrastructures (which are expensive, cannot be deployed on every road, and provide only limited information), EZCab uses a vehicle-to-vehicle approach whose key benefits are scalability and practicality. Our other prior work in the area of vehicular and mobile computing includes vehicular services over V2V [9], [10], adaptive traffic lights using V2V [11], and security and privacy [12], [2].

Our work in the “Experimental Vehicles, Intelligent Intersection & Instrumented Car” Project, has developed a roadside station and multiple car testbed for evaluating MAC and network protocol performance at various speeds. This work includes the “cross layer” of radio, MAC, and network layer (routing and multicast) protocols in the presence of obstacles [13]. The WHYNET Project, has implemented a six car Campus testbed to enable experiments in routing, urban sensing, and emergency recovery [14], [15], [16].

VII. CONCLUSIONS AND FUTURE WORK

In this position paper, we have made a case for prioritizing lanes on highways in order to provide congestion free travel during periods of high volume. We have described the design rationale of an intelligent lane reservation system. We have identified the various components of the system and the infrastructure requirements. The next step is to evaluate this system through a vehicular simulator, which is currently under development, and compare the various design options. We plan to prototype this system in the near future and

discuss deployment opportunities with the department of transportation.

VIII. ACKNOWLEDGMENTS

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